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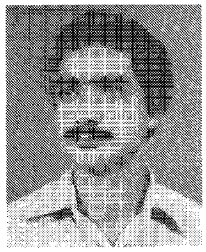

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A Review of SAW-Based Direct Frequency Synthesizers

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Abstract—**Many new electronic systems, including spread spectrum links, require frequency synthesizers capable of providing accurate signals of high spectral purity, and must be able to change frequencies in fractions of a microsecond. Three such synthesizers based on comb generators, SAW filterbanks, and fast switches are reviewed. Each of these synthesizers can provide an output at approximately 1.3 GHz from one of over 200 frequencies of integral megahertz value.**

I. Introduction

SURFACE ACOUSTIC wave (SAW) components offer a compact cost-effective way to make a variety of components, including filters [1], delay lines [2], correlators [3], and frequency synthesizers [4]–[6]. This last application is the subject of this paper. In particular, a review of recent work on the use of SAW devices for obtaining fast-frequency hopping, direct frequency synthesis will be provided.

Direct synthesis [7] is useful whenever submicrosecond frequency hopping is required in combination with high spectral purity and frequency precision that is as good as the reference clock. To these features, SAW's add their traditional advantages of small size and moderate cost. The basic version of the direct SAW frequency synthesizer [8], [9] consists of a comb generator and switchable filterbank as shown in Fig. 1. The comb spectrum is simultaneously fed to all channels of the filterbank which sorts them according to frequency. Since the tones present at the filter outputs are continuous waves (CW), they can be switched

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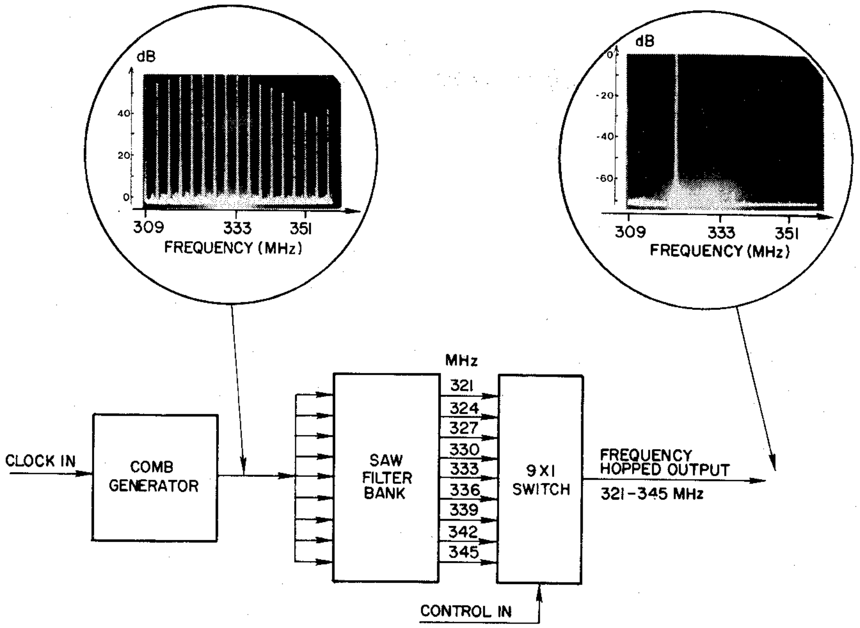

Fig. 1. Schematic illustration of a single channel direct SAW synthesizer. Insets show frequency spectra at indicated points.

TABLE I

SYNTHESIZER DESIGN GOALS	
Frequency range	~ 1280-1535 MHz
Frequency spacing	1 MHz
Spurious tones	63 dB down
Noise (dB/Hz)	120 dB down
Switching speed	200 nanoseconds
Temperature Range	-54°C to 80°C

as fast as the switches themselves.

Since an individual SAW filter is required for each output tone, the basic implementation is useful when a moderate number of frequencies must be synthesized. If a large number of tones are required, alternate approaches are recommended. For example, several basic synthesizers can be used and mixing of their outputs can be employed [10]. This type of synthesizer will be discussed in detail in Section II. Another possibility is the use of an iterative synthesizer [11]. Here a relatively small number of CW tones are multiplexed to several switches and sequential dividing and mixing is used to obtain the desired output tones. Examples of iterative synthesizers will be provided in Sections III and IV. In one case [12], only four tones and four 1×4 switches were necessary to obtain 256 output frequencies.

Each of the synthesizers to be described in the next sections was designed toward the goals summarized in Table I. These goals for overall performance lead, in turn, to individual requirements on each component. Some of the major design considerations were efficient generation of comb spectra while achieving high spectral purity and locking to the reference frequency, high isolation in the SAW filterbanks, switches, and packaging, and high signal-to-noise ratios.

The first of the three synthesizers was developed [4], [6], [8]–[10], [15] by the authors in order to demonstrate the concept. It served as a general prototype for the others which were developed at the Hughes Aircraft Company and at TRW. The later designs represent more compact, lower cost versions.

II. Switched SAW Filterbank Synthesizer

This synthesizer has been previously covered more extensively in the literature [4], [6], [8]–[10], [15]. As discussed above, the requirement for the generation of approximately 256 tones dictates a more efficient system than could be achieved by using the scheme of Fig. 1 with 256 filters. By starting with three direct synthesizers, and mixing together two sets of 9 tones and one set of 3 tones, a capability of $9\times9\times3=243$ tones can be achieved [6] as shown in Fig. 2. The switched SAW filterbank synthesizer consists of *two* 9-tone direct SAW synthesizers plus a 3-tone direct synthesizer using phase-locked loops. For convenience, the synthesizer is divided into three sections. The *source* section contains comb generators covering 321–345 MHz in 3-MHz increments and 360–468 MHz in 12-MHz increments, plus multipliers and phaselocked loops which produce 1984-, 1985-, and 1986-MHz tones. In addition, it has the 3×1 switch which chooses among the latter sources. The *SAW and switch* section includes the two 9-tone SAW filterbanks, each of which is connected to a 9×1 switch, just as in Fig. 1. The *output or mixer* section contains amplifiers, filters, two mixers, and a frequency doubler. Use of the mixing scheme, plus frequency doubling to achieve the high-frequency set of tones, allows the SAW filters to

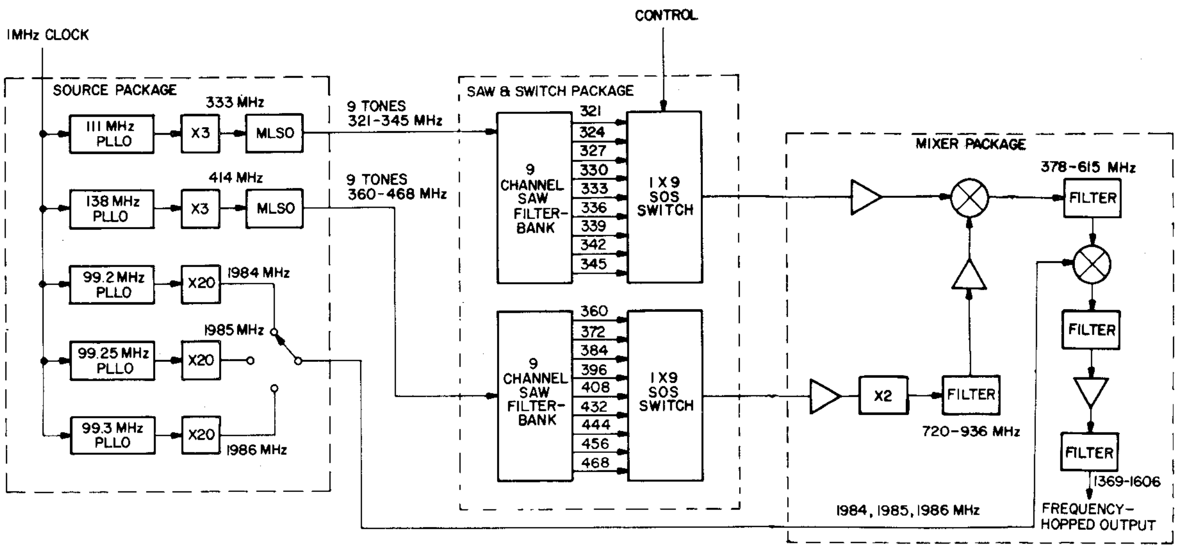

Fig. 2. Block diagram of complete switched filterbank synthesizer.

operate in the 321–468-MHz range where transducer linewidths are no less than 0.8 μm wide (for double electrodes on ST Quartz at 468 MHz).

A. Source Section

All the signals which appear at the output of the frequency synthesizer arise from combining tones which originate in the source section. These must be as stable and accurate as the clock. On the other hand, any noise or close-in spurious signals present in the source section will also be present in the output, putting very tough specifications on this circuitry. For the synthesizer under discussion here, the source package consisted of two comb generators and the 1984–6-MHz sources. The 1984-, 1985-, and 1986-MHz sources operate by using phased-locked loops at approximately 100 MHz locked to the 1-MHz clock, then performing a final multiplication to the required frequency [13]. As the comb sources were crucial and complex parts of the synthesizer, two approaches were investigated. In the straightforward electronic approach [13], the 1-MHz clock was multiplied to either 3 or 12 MHz to yield the appropriate tone separation, then this higher frequency signal was amplified and used to drive a step recovery diode to generate the required comb spectrum.

An alternative approach for the comb generation is the mode-locked SAW oscillator [14] (MLSO) shown in Fig. 3. The input shown is the 1-MHz clock. Although this SAW based comb generator is smaller, lighter, and consumes less power than the more conventional electronic approach, additional work is required to achieve stable operation over a wide temperature range. For the results reported here, the step recovery diode source produced the high-frequency comb, and the MLSO was used for the low-frequency one.

B. SAW and Switch Section

The switched SAW filterband synthesizer used two high performance 9-channel switchable SAW filterbanks on temperature compensated (ST cut) quartz. Each filter consists of a length weighted transducer and a withdrawal weighted transducer [1]. In order to achieve the extremely high out-of-band rejection shown in Fig. 4, many factors were optimized and second-order effects were controlled [15].

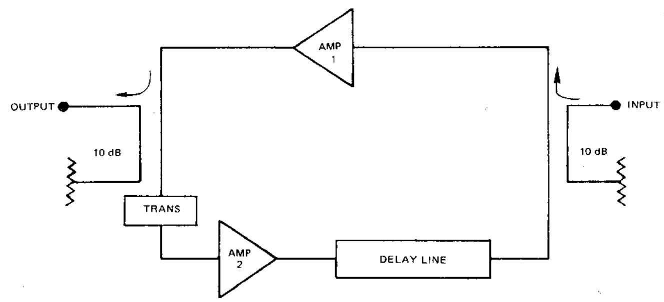

Fig. 3. Schematic diagram of a mode locked SAW oscillator (courtesy of United Technologies Research Center).

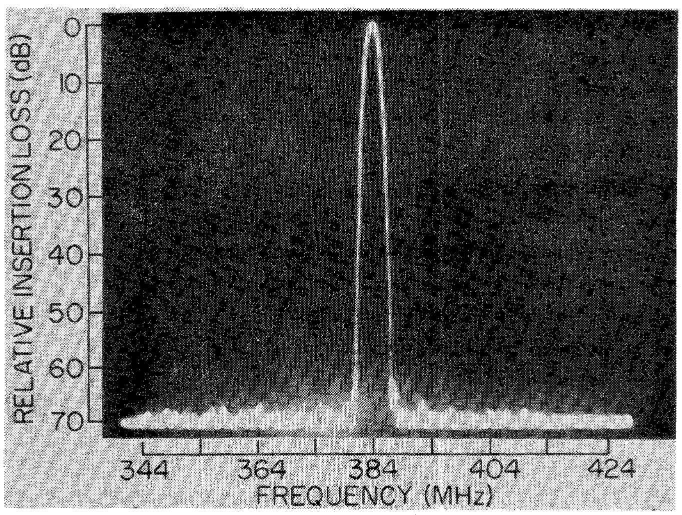

Fig. 4. Frequency response of SAW filter needed to implement the switched filterbank synthesizer.

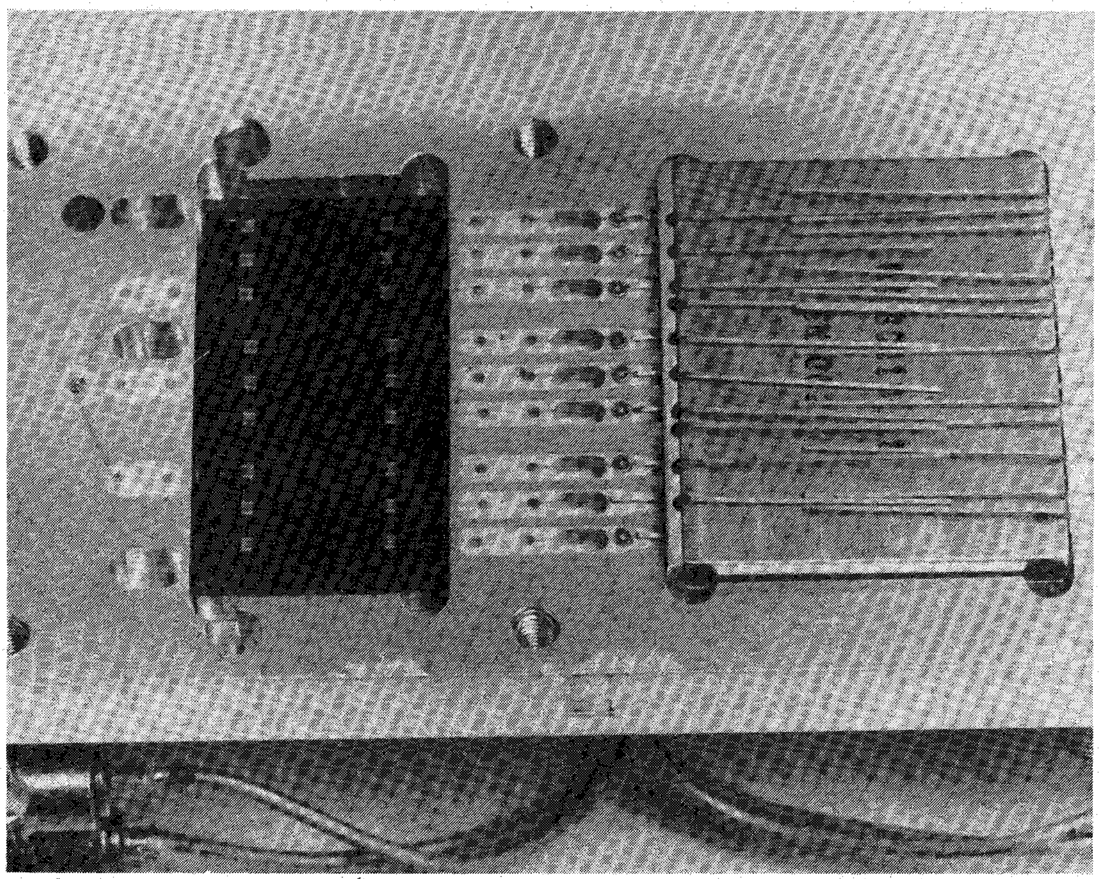

Fig. 5 Photograph of switched SAW filterbank. From left to right: input, tuning inductors (potted), SAW chips with interconnected input transducers and individual output transducers, output tuning inductors (potted), space for tuning capacitors (not used), test outputs (not used), and switch (2.4×2.8 cm).

Each of the two filterbanks operates as a single-input single-switch selected output device. This required interconnection of the 9-input transducers. The goals of 1) insertion-loss minimization, 2) insertion-loss uniformity among channels, and 3) small size and low cost, were achieved by choice of an optimized series-parallel interconnection scheme [4], [15]. Optimization was particularly important for the high-frequency bank, with 26-percent bandwidth. Overall performance for this bank included a mean insertion loss of 25.8 dB, with worst case spurious tone 57.5-dB below the desired output. Ten percent of the spurious tones were stronger than the specified 63-dB down. In the low-frequency filterbank, worst case spurious was 61.5-dB down with three percent of the spurious tones failing to meet the specified 63-dB down. Typically, the spurious tones were 68-dB down.

Two switches were investigated—one approximately 2-ns switch [16] with a 16.5-dB insertion loss, and a 250–400-ns one [17] with 1.5-dB insertion loss. The latter was used, and is incorporated in the switched filterbank shown in Fig. 5.

C. Output Section

The output or mixer section is the right-hand block of Fig. 2 (labeled MIXER PACKAGE). The rigorous specifications on spurious rejection and low noise imposed constraints on the output section. Thus, high quality double-balanced mixers and filters with high out-of-band rejection were used, and careful attention was paid to power levels.

The original choice of the frequencies to be generated and mixed was optimized to minimize the mixer-generated spurious signals [10], [18]. An analysis of the spurious tones produced was carried out. Note that the high-frequency switched filterbank output is doubled before mixing to yield the required intermediate frequencies. Use of the doubler reduced by a factor of two the required operating frequencies of the high-frequency filterbank and the associated 1×9 switch. On the other hand, as multiplication of a signal by N decreases signal-to-spurious ratios by at least $20 \log N$, there is a 6-dB noise and spurious penalty.

D. Overall Comments, Switched SAW Filterbank Synthesizer

The advantages of the switched SAW filterbank synthesizer are those given in the introduction. Also, as stated previously, reasonably good spurious suppression was achieved in the filterbank switch section. However, due to a combination of nonideal doubling, leakage of comb tones into later portions of the synthesizer, and the limiting used to level the hopped output, the overall spurious performance has degraded to approximately 47 dB, as given in Table II. A synthesizer tone at 1546 MHz is illustrated in Fig. 6. The spurious performance, while failing to meet the

TABLE II

	GOALS	RESULTS		
		SWITCHED FILTERBANK SYNTHESIZER	TWO-MIXER ITERATIVE SYNTHESIZER	FOUR-MIXER ITERATIVE SYNTHESIZER
FREQUENCY RANGE (MHz)	1280-1535	1369-1606	1277-1538	1280-1538
TONE SPACING (MHz)	1	1	1	1
SPURIOUS LEVEL (dBc)	-63	-47	-55	-43
NOISE LEVEL (dBc/Hz)	-120	-110	-120	N/A
SWITCHING SPEED (Nanoseconds)	200	<100	<100	25
SIZE	Small	4×10^{-2} cu m rack	1.4×10^{-2} cu m board	2×10^{-3} cu m

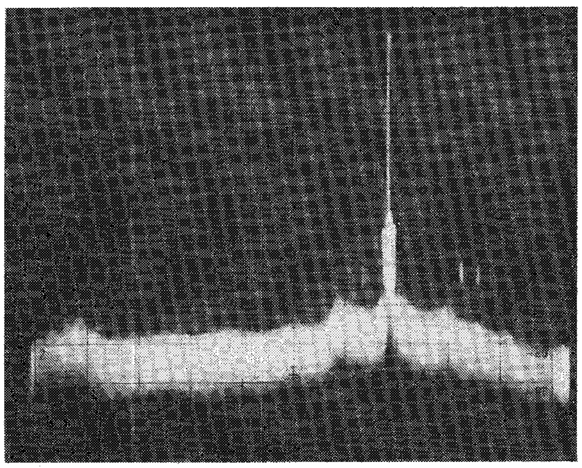

Fig. 6. 1546-MHz output tone from switched filterbank synthesizer. 10-dB/div vertical scale. 30-MHz/div horizontal scale.

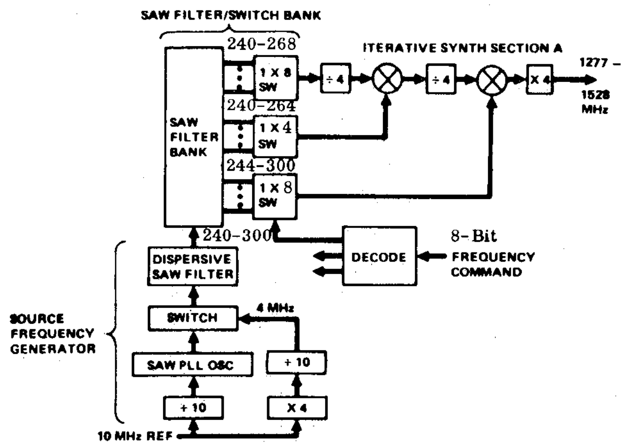

Fig. 7. Simplified block diagram of two-mixer iterative synthesizer (courtesy of Hughes Aircraft Company).

−63-dBc specifications, is very adequate for many synthesizer applications and is readily improvable by packaging and shielding modifications.

III. Two Mixer Iterative Sythesizer [19]

In choosing designs for frequency synthesizers, the iterative approach can yield a larger number of outputs per input frequency. In the synthesizer reviewed here, two stages of divide-and-mix are used to obtain 256 output frequencies from an initial 12 tones. This is illustrated in Fig. 7. Although the other 2 synthesizers use doubling at some stage, this is the only one which uses quadrupling. To minimize the difficulties of dealing with L-band signals, the synthesized output was chosen to be 319–383 MHz, followed by quadrupling to the required band. The 12-dB penalty in higher required spurious and noise rejection was accepted.

A. Source Section

A comb generator based on a step recovery diode has the disadvantage of generating significant energy in low-frequency harmonics. A more efficient approach is to generate a CW signal at the center of the desired band, then to gate coherently this tone at the required channel spacing. This yields a comb spectrum with its energy concentrated in the required band. For the present example [19], a 268-MHz signal gated at a 4-MHz pulse repetition frequency yields the required 240–300-MHz, 4-MHz spaced comb spectrum. To avoid a high peak-to-average power ratio in the time domain structure of the comb (which increases power requirements and therefore amplifier costs), a SAW chirped filter was placed immediately after the gated source. This levels the time domain signal while retaining the desired comb structure in the frequency domain [19].

B. SAW Filterbank

In order to obtain the required spurious suppression in the frequency domain, the straightforward approach of cascading two individual filters was adopted for this synthesizer. A simple matching network was used between the two devices as shown in Fig. 8. The SAW substrate was ST cut quartz [20], and each filter consisted of a length weighted and a withdrawal weighted transducer. The power division

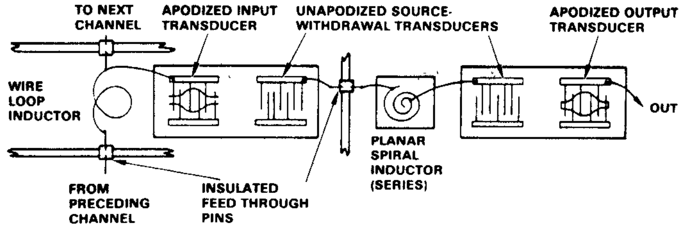

Fig. 8. Dual SAW filter configuration used in two-mixer synthesizer (courtesy of Hughes Aircraft Company).

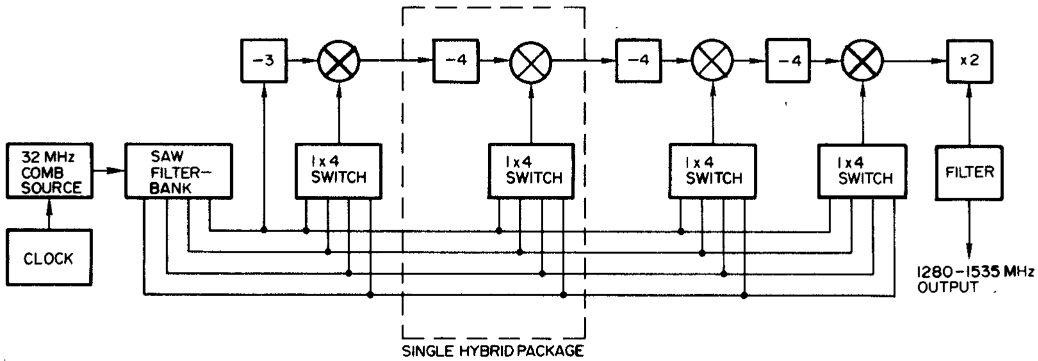

Fig. 9. Simplified block diagram of four-mixer iterative synthesizer (redrawn from figure supplied through the courtesy of TRW).

from the comb generator to the 12 filter channels was accomplished using the constant-K ladder multiplexing scheme [21]. This has the advantage of allowing each input to have a grounded electrode, thereby reducing capacitive electromagnetic feedthrough. In addition, the constant-K ladder operates well in the presence of filter parasitic resistance.

C Switch

This synthesizer has the most complex switching requirements of the three. Twelve CW signals have to be partitioned to the three mixer ports in two subsets of 8 and one of 4, as is shown in the two portions of Fig. 7. A multipole RF switch was obtained from the same vendor [17] as for the previous synthesizer. It was configured as two 8PST and a 4PST switch to carry out the above functions. Off isolation was 60–80 dB, compared with the 90 dB required to achieve full −63-dBc spurious performance.

D. Output Section

Commercially available amplifiers and doublers were cascaded to yield the required output. An amplitude sensor and negative feedback to a variable diode attenuator were used to level the output.

E. Overall Comments, Two-Mixer Iterative Synthesizer

A breadboard implementation of the frequency synthesizer shown in Fig. 8 was successfully fabricated and tested. Although some problems were encountered in meeting the spurious suppression goals, ~51-dB levels were achieved, the feasibility of the architecture was clearly demonstrated. The potential low cost of a SAW-based synthesizer can be illustrated by noting that the three switches (packaged together) would represent over one-half of the cost of this synthesizer in volume production.

IV. Four-Mixer Modular Iterative Synthesizer [12]

This approach [12] is a highly efficient design, yielding 256 tones with only four source frequencies. In fact, only two clock-coupled phase-locked loop oscillators are required. Further, the synthesizer uses four identical amplifier-divider-mixer modules with the attendent economies of scale. The overall design is illustrated in Fig. 9.

A. Source Section

The four-tone, 32-MHz spaced comb spectrum applied to the SAW filterbank is derived in a unique way [12]. Two phased-locked-loop oscillators, each coupled to a 40-MHz clock, generate tones at 512 and 544 MHz. These are then combined and amplified nonlinearly which yields the remaining two tones at 480 and 576 MHz as intermodulation products.

B. SAW Filters

The SAW filters used for this synthesizer [12] differ from the cases described above mainly in the choice of SAW substrate. YZ lithium niobate was chosen for its high coupling coefficient which results in a wider bandwidth for a given insertion loss. The high-temperature coefficient of lithium niobate was no disadvantage in this case since the 32-MHz spacing allowed a sufficiently wide passband to incorporate tolerances for both temperature and manufacturing variations. As in the previous iterative synthesizer, two filters in series provided the necessary sidelobe suppression; however, in this case an amplifier was included between the two devices.

Each filter has an input transducer of thinned single electrodes, and an apodized weighted $\sin X/X$ output transducer which is designed with double electrodes at one-third the actual operating frequency. That is, the output transducer is operated at its third overtone. Finally, multiplexing of the comb input to the four channels of the filterbank is accomplished by series-parallel interconnection.

C. RF LSI Switch

To achieve the performance required, yet keep size, weight, and cost to a minimum, a custom radio frequency, large scale integration (RF LSI) 1×4 switch was developed [12]. It consists of an amplifier in each of the four channels which can be biased off and on, with less than 10 ns switching time. All on-chip circuitry is differential. Although overall performance was quite satisfactory, achieving synthesizer -63-dB spurious would require an additional iteration to improve isolation by approximately 20 dB.

D. Amplify-Divide-and-Mix Module

As with the switch, four amplify-divide-and-mix circuits are required for each synthesizer. Thus it was of particular value to develop [12] a hybrid module for these functions. The developed version is programmable for either divide by 3 or 4, in order to fit in any position in the overall synthesizer. Isolation was somewhat of a problem here also but could be improved in another iteration. A combined 1×4 switch and amplify-divide-and-mix module comprise one complete section of the iterative synthesizer.

E. Overall Comments, Four-Mixer Iterative Synthesizer

The complete synthesizer, consisting of the above components plus a limiting output amplifier, successfully met design goals except that spurious levels were only $\sim$43-dB down. As mentioned, improvement here could be expected on additional iterations. Enough was learned to allow for both improved layout on each chip and improved packaging. The most promising feature of this approach [12] is the use of four identical switch chips and amplify-divide-and-mix chips to achieve cost economies. This, in turn, makes it feasible to build custom chips. It is estimated that this synthesizer could be built at the lowest cost of the three discussed here.

V. Summary and Conclusions

Three different SAW synthesizers developed toward the same goals by three different design teams have been reviewed. The iterative synthesizers use fewer source tones than the switched filterbank implementation but require post multiplication. Only intermediate multiplication in one path is required in the switched filterbank case. Since multiplication by N degrades noise and spurious by $20 \log N$ (6 dB for doubling and 12 dB by $\times4$ multiplication), we have a partial explanation as to why two filters in series are used in the iterative cases compared to only one very high performance filter in the switched filterbank synthesizer. A second reason is in the lower manufacturing costs of the less rigorous filters.

The limitation of divide by 4 iterative synthesizers to approximately 14-percent frequency coverage [7] (for the case of 2:1 shape factor sharp cutoff filters) to 29 percent (for rectangular cutoff filters) was not a particular problem in this case since only 16–18-percent coverage was necessary. However, the sharper cutoff filters slow tone-switching response time. In comparing the various architectures it should also be noted that currently available divide-by-four units have a 90 degree phase ambiguity; thus iterative synthesizers cannot be used if phase coherence is required.

A general summary of results is given in Table II. The best overall performance was demonstrated by the two-mixer iterative synthesizer. The smallest size and lowest cost belong to the four-mixer architecture. The switchable SAW filterbank implementation was the original prototype direct SAW synthesizer thus accounting for its larger size. This architecture is useful when wide bandwidths must be covered with unambiguous phase resettability. We note that the low spurious levels desired were not achieved with any of the synthesizers, even though the performance achieved was excellent and satisfactory for most applications.

Acknowledgment

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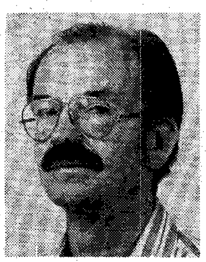

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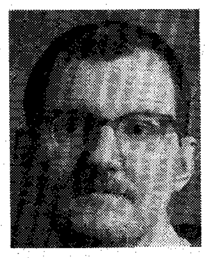

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